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Static And Dynamic Stability Analyses for Slopes of Chenab Railway Bridge Abutments

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Abstract: Slope stability is an issue of utmost importance in the Himalayas where the world's highest railway bridge is being constructed across the Chenab River in Jammu and Kashmir state of India. The bridge is part of Katra - Qazigund section of the ongoing Udhampur-Srinagar-Baramulla-Rail-Link (USBRL) project as a part of the ambitious plan of connecting remote areas of Jammu and Kashmir with the rest of the country by Indian Railways. The height of the slope and the presence of foliation joint with two sub vertical joint sets in dolomitic limestone make the rock slopes of bridge abutments critical for stability verifications. This paper presents an approach to study the stability of slopes with different joint sets having different strength parameters. The stability analyses of the slopes have been performed using Limit Equilibrium, Finite Element and Discrete Element methods of modelling through Slide, Phase$_2$ of Rocscience® and UDEC of Itasca®.

Keywords: *Slope stability; Joints; Limit Equilibrium Method; Finite Element Method; Discrete Element Method*

INTRODUCTION

Slope instability has been resulting through ages whenever human or natural forces havedisturbed the equilibrium of natural slopes. The change in topography, ground water forces, seismic loads or external loads and loss of ground strength due to water, weathering are the key causes of slope instability. Increasing railway and highway projects in mountainous terrains across the country have increased the need for engineered cut slopes consisting of earth materials of varying geo-mechanical behavior and geotechnical properties.

The stability analysis and stabilization measures recommendation require detailed study of slope geometry, geology, hydrology, geotechnical parameters of rockmass and joints and seismology of the region. The geo-mechanical model for the analyses must accuratelyrepresent the actual site conditions, load condition and ground behavior.

A slope can fail either when the stresses are excessive of shear strength of rockmass or due to relative displacement between the blocks/wedges formed by dominant discontinuities. Hence, stability of jointed rockmass slope is analyzed based on behavior of rockmass as continuum using Limit Equilibrium Method (LEM) and Finite Element Methods (FEM) and based on behavior of dominant joints, bedding planes and faults using Discrete Element Methods (DEM). This presents the stability analyses of the slopes of Chenab Railway Bridge Abutments using these methods.

PROJECT OVERVIEW

The 359 m high and 1315 m long Chenab Railway Bridge between Bakkal and Kauri in the Reasi district of Jammu and Kashmir is the part of Indian Railway's megaproject, Udhampur Srinagar Baramulla Rail Link (USBRL). The bridge consists of total 18 piers, 4 piers (P_{10}, P_{20}, P_{30} and P_{40}) on left slope and other 14 piers (P_{50} – P_{180}) on the right slope (Figure 1). The natural slopes with inclination 50° – 60° are reprofiled for construction of piersand abutments.

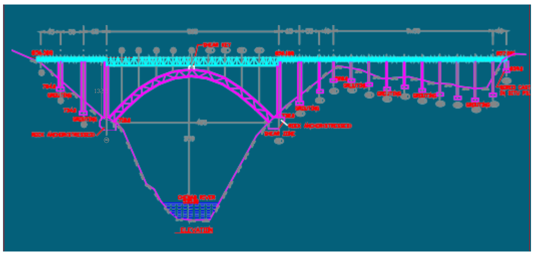


Figure 1 Layout of Chenab Bridge

The major rock type encountered in both the abutments (Chainage 50.383 Km 51.200Km) is dolomitic limestone of Sirban formations with different degree of fracturing, weathering and no major shear zones. Table 1 summarizes the geotechnical properties of intact dolomite rock found in Chenab region.

Table 1 Intact Rock Properties (Rao et al., 2012)

Property	Value
Density	2.762 g/cc
UCS (dry)	160.50 MPa
Tensile strength	16.86 MPa
Point Load Index	14.12 MPa
E_t (50)	4.41 * 10^4 MPa
Poisson's Ratio	0.22
Cohesion	22.50 MPa
Friction Angle	58°
Deere Miller Classification	CM/BM
Hoek-Brown constant (m_i)	40

The strata are characterized by prominent sub-horizontal foliation joint and two sub vertical joint sets with few random joints (Figure 2 and Table 2).

Figure 2 Close up view of the joints in dolomitic rock on left side (Rao et al., 2012)

Table 2 Geo-structural parameters of discontinuities on the left and right abutments (Rao et al., 2012)

Feature	Strike	Dip	Dip Direction
Foliation Joint (Joint-1)	N140° E	21°	N050° E
Joint-2	N150° E	65°	N240° E
Joint-3	N075° E	80°	N165° E

The joints are rough, planar and unaltered with occasional infilling and very minor surface staining. The joint properties for Joint Set 1, 2 and 3 considered for numerical modelling are presented in Table *3*.

Table 3 Joint Property (Rao et al., 2012)

Property	Joint 1	Joint 2	Joint 3
Dip	21	65	80
Dip Direction	N050°E	N240° E	N165° E
Strike	N140° E	N150° E	N075° E
Cohesion	0	0	0
Friction angle	38°	38°	38°
Persistence (m)	2.26	2.716	0.53
Gap length (m)	3.26	3.716	1.53
Spacing (m)	1-10	10-100	20-100
K_n (KN/m^3)	36692	36692	36692
K_s (KN/m^3)	29090	29090	29090

Rock mass properties as obtained from in-situ tests in drift are listed in Table 4.

Table 4 Rock mass properties (Rao et al., 2012)

Property	Value
Unit weight (kN/m^3)	27.62
Bulk Modulus (Pa)	5.055*10^{10}
Shear Modulus (Pa)	3.792*10^{10}
Hoek Brown constants, m & s	4.706, 0.00127
Cohesion (MPa)	1.40 (L), 1.41 (R)
Friction angle (°)	44.42 (L), 44.61 (R)

STABILITY ANALYSES

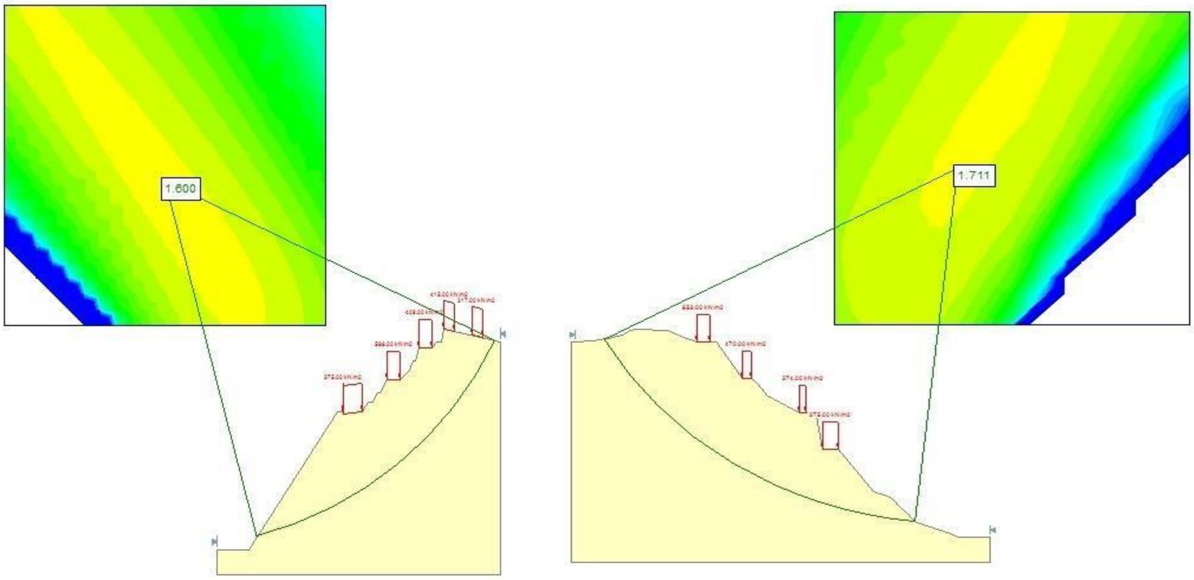
The natural hill slope was not uniform in all directions. Thus, the analysis of slopes at two abutments only along the bridge alignment is not sufficient to understand the behavior of the slope under different loading conditions (Pier loading, Seismic loading etc.). Hence, slope profiles at different angles w.r.t. to rail alignment, 0°, 20°, 30° and -20°, are analyzed for complete study of the two abutments. Apparent dip angles for the three joint sets are also evaluated along the different directions.

The limit equilibrium, continuum and discontinuum analyses are performed for both static and seismic cases. The project is located in Seismic Zone V and the seismic coefficients for pseudo-static analysis, α_h and α_v, are conservatively chosen equal to 0.3 and 0.2, respectively.

1.1 Limit Equilibrium Analysis

The limit equilibrium analyses for all slopes in different directions at left and right abutments are carried out in Slide software of Rocscience® group using Bishop Simplified method. The software computes the circular failure mechanism with the lowest Safety Factor (SF) based on research are defined by user in terms of possible centers of the failure surfaces and range of radii.

The safety factors obtained for all cases are more than required SF in static and seismic conditions. The highest Safety Factor values were obtained for the slope profile along 30° from central alignment for both left and right abutments. For right excavated slope, min SF value (1.6) came at 0 degree under pier andseismic loading. For left excavated slope, min SF value (1.711) came at -20 degree under pier and seismic loading (Figure 3, Table 5 and Table 6).



(a) (b)

Figure 3 Slide output for right abutment slope at 0° (a) and left abutment at -20° (b) under pier and seismic load

Table 5 Safety Factor for left abutment slopes under pier and seismic loads

Slope alignment	0º	20º	30º	-20º
Safety Factor	1.75	1.73	1.76	1.71

Table 6 Safety Factor for right abutment slopes under pier and seismic loads

Different parametric study	0º	20º	30º	-20º
Safety Factor	1.60	2.31	2.62	2.22

1.2 Finite element analysis in $Phase_2$

The FEM software of Rocscience® Group, Phase2, has been used for modeling the three joint sets in the slopes with properties of joints as summarized in Table *1* and Table *3*. Themodel for left slope at 30° under pier and seismic loads is presented in Figure 4. Roller boundary conditions are applied on lateral sides to restrict movements in x direction and thebase boundary is fixed in both x and ydirections.

The software uses Shear Strength Reduction (SSR) method for determining Strength Reduction Factor (SRF), equivalent to SF, of slopes. The SRF is defined by following equation.

$$SRF = \frac{\tan \Phi^F}{\tan \Phi_f^F} = \frac{c^F}{c_f^F}$$

Where Φ_f' and c_f' are the effective stress strength parameters at "failure", or the reduced strength. The strength reduction approach generally uses the same SRF for all material and for all strength parameters, so that the stability factor reduces to one number in theend. This means c and Φ are reduced by the same factor.

The SRF for all the slope models are more than required SF for static and seismic cases. For right slope, maximum (2.55) and minimum (1.00) SRF values are found for 30° and -20° plane, respectively. For left slope (

Figure 5), maximum (1.84) and minimum(1.04) SRF values are obtained for 0° plane and 30° plane, respectively. The SRF value for slope profile along the bridge alignment is greater than one for both left and right slopes which confirms the stability of slope. The results for all cases are summarized in Table 7 and Table 8 for left and right slopes, respectively.

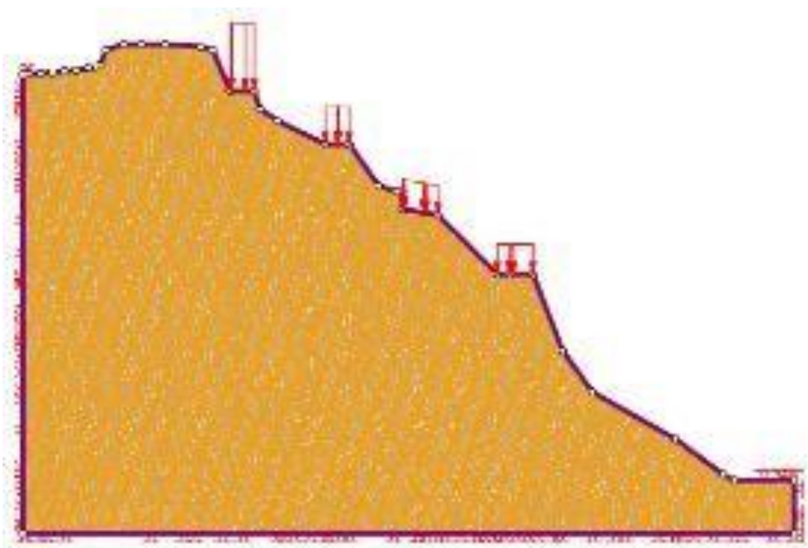


Figure 4 Phase$_2$ model for left slope at 30° under pier and seismic loads.

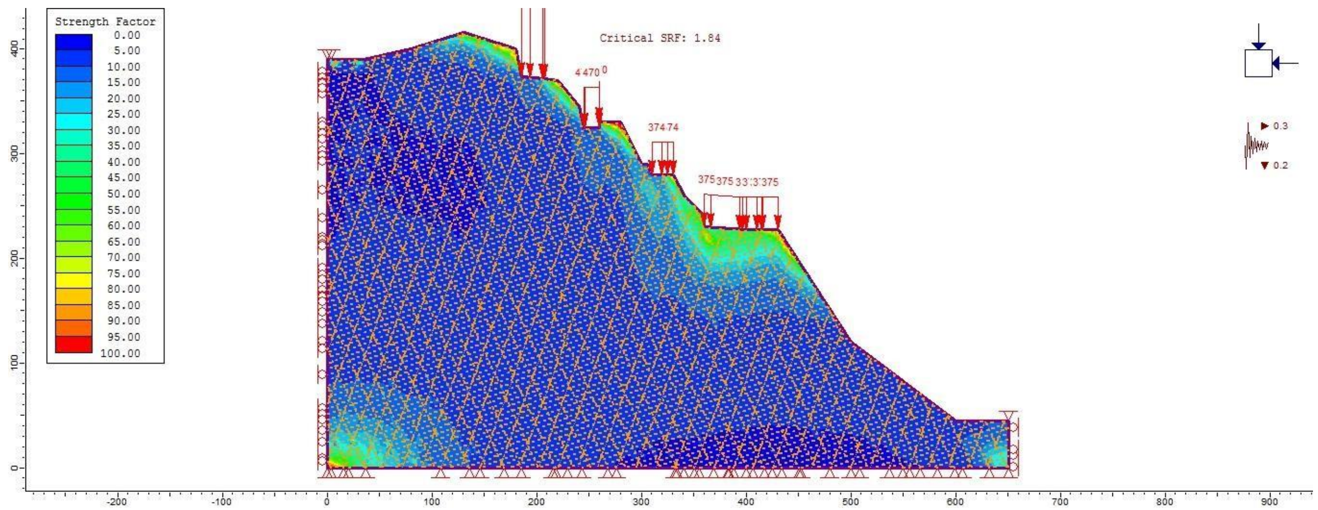


Figure 5 Phase$_2$ output for right left abutment at -20° under pier and seismic load

Table 7 Phase$_2$ results: Critical SRF for left slope under pier and seismic loads

Slope alignment	0º	20º	30º	-20º
Critical SRF	1.84	1.08	1.04	1.55

Table 8 Phase$_2$ results: Critical SRF for right slope under pier and seismic loads

Slope alignment	0º	20º	30º	-20º
Critical SRF	1.95	1.97	2.55	1.00

1.3 Discontinuum Analysis in UDEC

The analyses are carried out using UDEC, atwo-dimensional discrete element method software of Itasca® group. The software represents the discontinuous medium (such as jointed rockmass) as an assemblage of discrete blocks. The discontinuities act as boundary conditions between blocks and large displacements along discontinuities and rotations of blocks are allowed (Itasca Manual, 2008). The joint sets in UDEC are treated as discontinuities between intact rock while in Phase$_2$ joints and intact rock are treated as a continuum. Total 8 slope profiles are modelled in UDEC and pier loads are applied successively, left slope at 20° model is given in Figure 6. Maximum X and Y displacements are obtained, and the total displacement is obtained by the vector sum of the X and Y displacements.

For left slope, minimum SF is obtained for slope at 30° and for right slope, 0° slope has minimum SF (Table 9 and Table 10). All the slope profiles are stable as the SF is greater thanone for all the cases.

Maximum horizontal displacements are observed below the Piers P_{40} and P_{50} because maximum loads are applied by these two piers. Maximum vertical displacements are on the piers located at the top of the slope as the confining stress is least on the top (Figure 7).

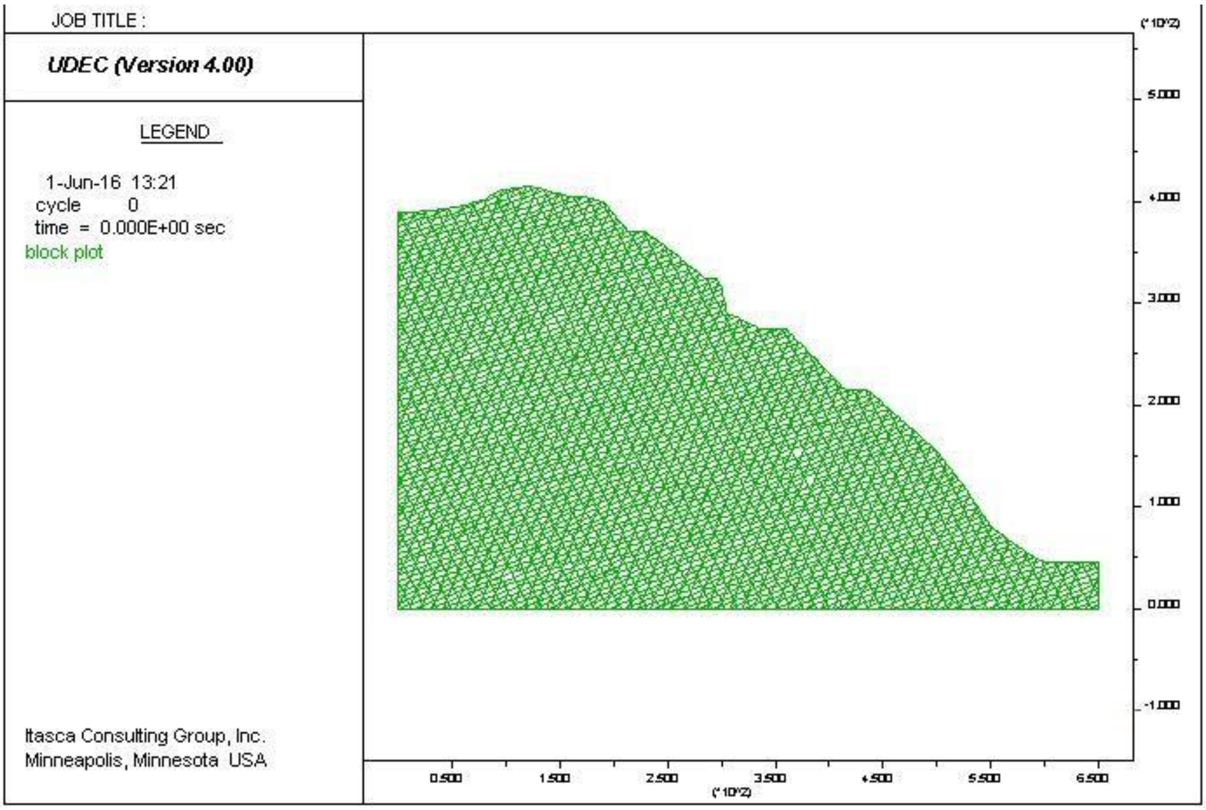
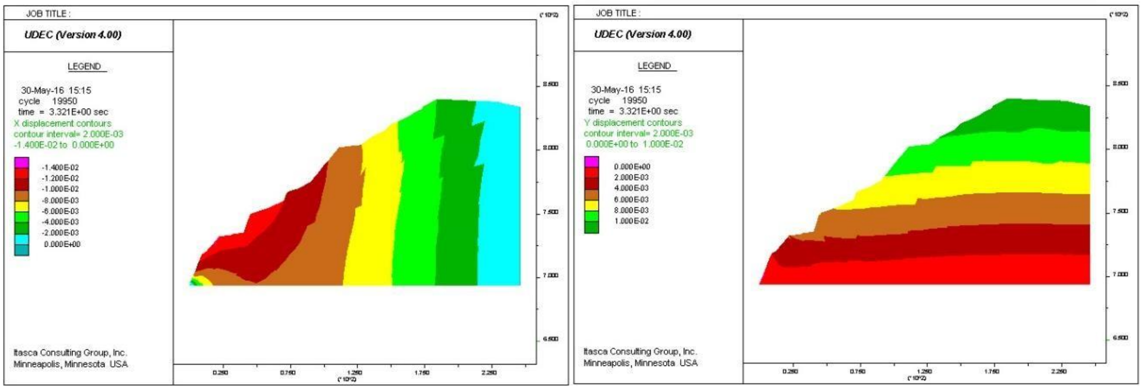


Figure 6 UDEC model for left slope at 20°



(a) (b)

Figure 7 X and Y Displacement contours for right slope at 30° under pier loads

Table 9 UDEC results: SF for left slope under pier load

Slope alignment	0°	20°	30°	-20°
SF	1.64	1.47	1.44	2.51

Table 10 UDEC results: SF for right slope under pier load

Slope alignment	0°	20°	30°	-20°
SF	1.44	1.89	2.51	1.65

CONCLUSIONS

The safety factors obtained using Slide for all the slope configurations are from 1.71 to 1.76 for left abutment slope and from 1.60 to 2.62for right abutment slope. The safety factors obtained using $Phase_2$ for all the slope configurations are from 1.04 to 1.84 for leftabutment slope and from 1.00 to 2.55 for right abutment slope. Safety Factor values obtained in Slide are more than the safety factor values obtained in $Phase_2$ because the effect of joints isnot considered in Slide. So, for analyzing the effect of discontinuities on slope stability,analysis is also carried out using a Discrete Element Method, Universal Distinct Element Code (UDEC). Safety Factor obtained for all cases was greater than 1. Hence, it can be concluded that the slope is safe for both right and left abutments. However, when actual slopecutting is done as per the final design requirement, primary and final support systems should be in installed for service life of theproject.

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